3.0 RESEARCH PLAN

3.1 Introduction to the Research Plan

In 1997, the South Florida Water Management District undertook an Estero Bay and Watershed Management and Improvement Plan, a multi-year project. The District's prime consultant, PBS&J, is charged with conducting an Estero Bay Assessment and an Estero Watershed Assessment. The watershed assessment will develop land and water management strategies to achieve water quality and quantity objectives for the Bay. Major assessment activities include physical descriptions of major features and current management practices, identification of water quality trends, ranking of potential pollution problem areas, and compilation of input data for a watershed model to evaluate management scenarios. A subsequent assessment phase utilizes modeling for scenario evaluation.

The Estero Bay Assessment will define water quality and water quantity objectives or pollution load reduction goals for the Bay and develop tools to evaluate the effects of watershed management techniques on the Bay. The Estero Bay Assessment involves the application of a logical protocol for designing study and management plans, to identify the types of pollutants and their impacts on estuarine environments. The first and present phase of the assessment will result in an Estero Bay Research Plan, based on management goals for the estuary. A subsequent assessment phase implements the research plan.

The Estero Bay Research Plan follows a method developed by Mote Marine Laboratory for the South Florida Water Management District's study of the St. Lucie River and estuary. The general method is described in Hayward *et al*. 1991a and 1991b, Estevez *et al*. 1991, and Estevez and Hayward 1992. Its application to the St. Lucie River system is described in Dixon *et al*. 1993, Dixon and Lowery 1993, Dixon *et al*. 1994, and Dixon and Hayward 1995.

First, goals are established for the Bay. Next, research questions appropriate to each goal are identified. Finally, analytical methodologies are defined to answer each research question. Taken as a whole, these tasks will comprise the Estero Bay Research Plan.

In Chapter 1, goals were identified through an analysis of existing laws, rules, policies, and other statements of social expectations for the Bay ("authorities"). These same sources provided insight to the valued ecosystem components of the Bay. Primary goals were developed around each major ecosystem component, and were written to meet criteria of meaningfulness, verifiability, and practicality. Secondary goals were identified around stressors known or suspected to play a significant role in regulating the condition of valued ecosystem components. Where needed, tertiary goals were identified in order to complete a causal link between valued ecosystem components, and management actions.

Goals from Chapter 1 are:

1.0. Restore the area, location, species composition, and condition of submerged aquatic vegetation (SAV-- sea grasses, rooted macrophytic algae) to pre-development conditions.

1.1. Bring proximate stressors of SAV (light, turbidity, salinity, exposure, biotic regulators, etc.) into ranges suitable for natural recolonization within areas of SAV extirpation.

1.1.1. Modify quantity and quality of freshwater inflows (surface water, ground water) as needed to relieve proximate stressors, within the context of natural geologic conditions in the Bay.

2.0. Create conditions of water quality necessary to increase the area of Estero Bay designated as Class II (shellfish propagation or harvesting) waters of the State, and permit some area of the Bay to be classified "approved" for shellfish consumption.

2.1. Bring proximate stressors of shellfish productivity and sanitation (pathogens, turbidity, salinity, exposure, biotic regulators, etc.) into ranges suitable for shellfish propagation and harvesting.

2.1.1. Modify quantity and quality of freshwater inflows (surface water, ground water) as needed to relieve proximate stressors, within the context of natural geologic conditions in the Bay.

3.0. Register the location, size, and duration of oligohaline habitat (salinity less than 10 parts per thousand) to pre-development conditions.

3.1. Modify quantity and timing of freshwater inflows (surface water, ground water) as needed, within the context of natural geologic conditions in the Bay.

Each of the three primary goals is meaningful in the context of Bay management. Each is verifiable through empirical measurement, and each is practical (achievable with existing technology). Primary goals address primary and secondary producers at the species, community, and habitat levels of biological organization. Each is traceable through intermediate goals to major management issues of freshwater inflow, and water quality.

The goals are used in this project task to develop empirical questions of two forms: one form seeks to establish status and trends of the estuary, and the other form asks questions regarding controlling processes. Such questions will guide the definition of analytical methods which, when implemented in the second phase of the Estero Bay Assessment, are expected to generate information useful in the definition of water quality and water quantity objectives or pollution load reduction goals for the Bay.

In Chapter 2, a number of specific research questions were developed for Estero Bay. Questions were combined to create a final list of 10 status and trend questions (STQ) and 9 causal process questions (CPQ), which are:

Status and Trend Questions

STQ. 1. What was the pre-development status of valued ecosystem components, in terms of
- a. SAV area, location, species composition, and condition;
- b. molluscan shellfish diversity, abundance, and sanitation; and
- c. oligohaline habitat area, location, species composition, and condition?

STQ. 2. What changes in valued ecosystem components have occurred from pre-development to modern time, in terms of
- a. SAV area, location, species composition, and condition;
- b. molluscan shellfish diversity, abundance, and sanitation; and
- c. oligohaline habitat area, location, species composition, and condition?

STQ. 3. What are the geographic and seasonal distributions (and other statistical properties) of measured values for the following stressors regulating valued ecosystem components, *specifically for open Bay waters:*
- a. water temperature, salinity, light attenuation, color, chlorophyll, mineral and organic turbidity, nutrients, current speed, wave energy, sediment structure, and tidal exposure values (for SAV), and
- b. also pathogen type and abundance, and dissolved oxygen (for shellfish)?

STQ. 4. How have statistical descriptors of present-day stressors changed over the period of available data, for SAV and shellfish in the Bay?

STQ. 5. What are the ranges, statistical distributions, and seasonal and spatial variations of present-day fresh water flow to the Bay, in terms of
- a. direct precipitation,
- b. gaged surface water discharge via waterways,
- c. ungaged surface water discharge via waterways,
- d. sheet flow,
- e. water table and surficial aquifers,
- f. confined aquifers, and
- g. permitted point and non-point source discharges.

STQ. 6. How have statistical descriptors of present-day fresh water flow changed over the period of available data?

STQ. 7. What are the geographic and seasonal distributions (and other statistical properties) of measured values for the following stressors regulating valued ecosystem components, *specifically for fresh water flowing to the Bay?*
- a. water temperature, salinity, light attenuation, color, chlorophyll, mineral and organic turbidity, nutrients, current speed, wave energy, sediment structure, and tidal exposure values (for SAV), and
- b. also pathogen type and abundance, and dissolved oxygen (for shellfish)?

STQ. 8. How have statistical descriptors of present-day SAV and shellfish stressors changed over the period of available data, in fresh waters flowing to the Bay?

STQ. 9. What are the present-day spatial characteristics of Bay sediments with respect to:
- a. age, provenance, transport, and deposition,

b. thickness, granulometry, and mineral composition,
c. organic content and oxygen demand, and
d. anthropogenic contaminant concentrations?

STQ. 10. What changes in sediment characteristics have occurred in recent times?

Causal Process Questions

CPQ. 1. What major physical changes have occurred in the study area, in terms of:
a. topography of the watershed, and
b. bathymetry of the Bay, its tributaries, or Gulf connections?

CPQ. 2. What are the present-day seasonal requirements and limits of valued ecosystem components (species diversity, shoot density, biomass, net production, etc. for SAV; diversity, abundance, and sanitation of shellfish; area, location, and species composition of oligohaline habitat), in statistically significant terms of the following stressors:
a. freshwater supply and tidal action (for oligohaline habitat);
b. water temperature, salinity, light availability, nutrients, current speed, wave energy, sediment structure, and tidal exposure values (for SAV), and
c. also pathogen type and abundance, and dissolved oxygen (for shellfish)?

CPQ. 3. Is physical recruitment a significant factor limiting SAV or shellfish abundance and production in the Bay? How?

CPQ. 4. Do biological interactions regulate valued ecosystem components more than abiotic stressors, specifically in terms of
a. epiphytic or drift macroalgal inhibition of SAV, and
b. predatory or parasitic inhibition of molluscan shellfish?

CPQ. 5. What statistically significant relationships describe the variation of SAV and molluscan shellfish stressors, as functions of the variation in values of freshwater inflow quantity, quality, and timing,
a. for stressor values measured in freshwater inflows, and
b. for stressor values measured in the Bay?

CPQ. 6. What changes in the quantity, quality, or timing of freshwater inflow must be achieved to relieve stressors regulating valued ecosystem components?

CPQ. 7. What are the sources, transport mechanisms, and residence times of pathogens in Bay waters and sediments?

CPQ. 8. What are the rates of pathogen bioaccumulation and depuration in Bay shellfish?

CPQ. 9. Is sea level rise a significant factor affecting valued ecosystem components in the Bay, in terms of,
a. regulating Bay geometry, elevation, sedimentation, or tidal exposure;
b. altering circulation, flushing, or salinity in open waters or tributaries, or
c. decreasing maximum depths of submerged aquatic vegetation?

3.2 Research Methods and Their Rationale

The present chapter describes fundamental research methods applicable to the research questions posed in Chapter 2, and provides a critique of each. Parts of the following sections have been adapted from previous reports on the general method (Hayward *et al*. 1991a and 1991b, Estevez *et al*. 1991, and Estevez and Hayward 1992), developed for South Florida Water Management District. Original reports may be consulted for complete method descriptions and critiques. The earlier reports dealt primarily with the detection and assessment of estuarine eutrophication, a primary concern for Estero Bay. Many of the methods also apply to other questions posed in Chapter 2, and others have been added to complete a description of needed methodologies.

On the Nature of Research Methods

Despite the variety of sciences and topics of study typically encountered in estuarine ecology, the methods of inquiry employed in any are often the same. A well-known example might be trend analysis. A geologist may look for changes through time in the sediment structure of an estuarine, whereas a hydrologist or chemist may be interested in patterns of change through time in freshwater inflow, or nutrient concentrations, respectively. Each investigator employs a general method of trend analysis, adapted to the questions and data of their particular science.

Estuarine scientists and managers have a palette of such methods (Table 1) from which to draw in designing and executing basic or applied studies. Experience with these methods in a variety of estuaries reveals merits and weaknesses of each which should be kept in mind when deciding the most appropriate approach to a problem. Some problems require the use of more than one method in order to achieve satisfactory results.

Method selection usually faces three scientific constraints and two practical constraints. Scientific issues include a) the availability of existing data (for some methods), and (for all methods) b) the design and collection of a set of data sufficient for statistical tests of significance, as in the testing of a hypothesis, and c) quality assurance. Methods dependent upon historical data can sometimes be used with "proxy" records that provide hindcasted estimates of requisite parameters. Quality assurance refers to the generation of data that meet pre-determined objectives for precision and accuracy. Projects attend quality assurance through the production and use of standard operating procedures, audits, and other measures. Practical constraints include the logistical difficulty of a project, and its cost. Some logistical requirements (simultaneity, for example) can be extremely difficult to achieve, and budget constraints require difficult choices to be made as a project progresses.

Table 1: Menu of Possible Approaches

APPROACH 1: STATISTICAL REFERENCES

A. STANDARDS
B. TREND ANALYSIS
C. INDEX METHOD
D. TYPICAL VALUE TECHNIQUES
E. NUTRIENT DILUTION

APPROACH 2: ECOSYSTEM COMPONENT ANALYSIS

A. INDICATOR SPECIES
B. VALUED ECOSYSTEM COMPONENT ANALYSIS

APPROACH 3: MODELS

A. NUTRIENT MASS BALANCE MODELS
B. BOX MODELS
C. HYDRODYNAMIC AND WATER QUALITY MODELS

APPROACH 4: EXPERIMENTAL

A. BIOASSAYS AND MESOCOSMS
C. WHOLE-SYSTEM MANIPULATIONS

APPROACH 5: COMPARATIVE

APPROACH 6: GEOGRAPHIC

A. SEGMENTATION
B. SPATIAL ANALYSIS (GIS)

3.3 Descriptions and Critiques

3.3.1 Standards

Description —
Local, state and federal laws prescribe values for water quality and other environmental attributes which may not be violated as a consequence of human activity. Laws and other authorities pertaining to Estero Bay were reviewed thoroughly in Chapter 1 of the Research Plan. Standards serve as end-points of allowable variation in a given attribute, and also as switches for regulatory attention. Many have been developed using comprehensive data bases, expert inputs, and years of experience, and so may be ascribed as having natural significance. Others, such as shellfish sanitation standards, are related more to the sanitation of food, and human health, than to natural resources or processes.

Regulatory standards tend to be used collaterally with other criteria in estuarine science. Studies of dissolved oxygen in estuaries, for example, would track instances when the State of Florida's average minimum of 5.0 mg/l or instantaneous standard of 4.0 mg/l are violated, but such studies are more likely to employ independent measurements of reduced species diversity or density as direct measures of resource impairment. Moreover, a number of estuarine concerns(such as nutrient enrichment) lack quantitative standards, shifting the burden of proof that harm has occurred or will occur to the investigator or resource manager. Standards are useful as trip-wires for regulatory corrective) actions but in general are not, in or of themselves, a tool of first choice in estuarine ecology.

Critique —
Performance: Standards work well in estuaries where science and management are problem-driven, as in the restoration of lost or impaired resources or values. In estuaries where the maintenance of existing, high-quality conditions is foremost, standards play a lesser role. In the former case, standards provide a useful reference point for studies, models, and management decisions.

Empirical Properties: Standards tend to be precisely defined because of their legal consequences.

Applicability: Standards address many common estuarine conditions, but not all. Standards are defined only qualitatively for nutrients for example, and their application to atmospheric deposition of nutrients is untried. Other common conditions important to estuaries, such as salinity variation (or freshwater inflow) tend to lack standards altogether. Standards are sometimes applied unequally, as in the case of exemptions given to certain governments, other parties, or activities.

Data Requirements: In many cases, laws define terms and conditions by which standards are to be expressed, as well as the precision or accuracy of data required to demonstrate violations.

Logistics and Costs: Logistics and costs tend to be low owing to the routine use of standards in environmental monitoring or law enforcement.

Diagnostic Features: Standards are unique insofar as they carry the weight of law, whereas other measures of ecological health or impairment tend to be scientific determinations made with independent sources of information.

Summary: Standards are useful benchmarks against which the condition of an estuary, as determined by scientific study, may be judged. Standards reveal nothing of processes responsible for their maintenance or violation.

3.3.2 Trend Analysis

Description —
Trend analysis is the attempt to determine whether the current value of some ecological or water quality parameter has changed over a period of time. It has similarities and relationships with time series analysis and intervention analysis, but it differs in being concerned, not with the mechanism of the change, but in the simple detection of the change and the description, if possible of the direction of the change. Detection of such trends in water quality parameters before the changes become extreme can lead to remedial action to correct the situation before damage to the ecosystem occurs.

The primary problem of trend detection is to decompose the long term record into its various components and sort the tendency or trend from other influences which might obscure it. Some such confusions might come from values which are spatially or temporally interdependent, which are non-normally distributed, which vary cyclically on a variety of time scales, or which are dependent on the flow or volume of fresh water entering the system. Frequently water quality time series have periods in which samples were not collected or the analysis failed, producing missing values. All these characteristics make trend detection in water quality difficult because such data do not conform to the assumptions of classical statistical methods.

Critique —
Performance: The primary problem of trend detection is to decompose a long term record into its various components and sort the tendency or trend from other influences which might obscure it. Some such confusions might come from environmental noise (seasonal or tidal variations in concentration or flow), spatial or temporal interdependence, censored data or failures in chemical analysis. Depending on the length of the record trends of varying sizes may be detected.

Empirical Properties: Because trend analysis is based on well known statistical techniques, it may be considered highly defendable and reliable. The confidence level and power may be determined precisely, but the power of these procedures to detect a trend is extremely sensitive to the length of the record.

Applicability: Trend analysis may be applied readily to data from tidal rivers, estuaries, lagoons, or forested coastlines. It can detect an historic change in the status of an estuary, and the direction of that change, given a sufficiently long record.

Data Requirements: Trend analysis requires a set of data, collected over a period of years, in a consistent and reliable manner.
The rules for the timing of the sample collection must be known (convenience sampling is not acceptable), the methods of sample collection, handling, shipment, preservation, laboratory measurement, and data reporting conventions (rounding and reporting limits) must be constant over the period of record. There can be exceptions to this requirement of constancy. Specifically, if changes have been documented to have no effect on the resulting data, or if changes result in known biases and these biases are subsequently corrected in the data undergoing analysis, then the procedures ... may be used to examine the data for trend (Hirsch *et al*, 1991:803).

Logistics and Costs: Trend analysis has high quality assurance needs for the consistency of the data. The proper application of the technique is usually unique to each system studied and requires some statistical sophistication, both in personnel and software. The required length of the data set (Hirsch *et al*. 1991, used 17 year records) makes adequate data collection expensive and prohibitive for answers to short term questions.

Diagnostic Features: Because of the length of data record required, trend analysis is probably more confirmatory than diagnostic.

Summary: Trend analysis can provide a highly reliable and defendable indication of change in nutrient concentration in an estuary. However, the requirement for a long term, consistent set of data and the potential for confusion in the data from multiple sources make it difficult to apply.

3.3.3 Indices

Water Quality Indices:

Description —
Indexing systems for water quality are an attempt to communicate the information content of a number of measurements of water quality variables in a form which can be readily comprehended by managers or lay persons. The venture is to produce just one number, or perhaps a few, that will integrate the data in a way that will readily indicate the suitability of the water for the intended use. Water quality indexing has been widely used but has not been accepted generally as an adequate means of communicating this information (Smith, 1990).

All indexing systems start with measurements of a group of water characteristics, or variables, considered to be indicative of its quality or suitability for its intended use. From these measurements a sub-index rating is determined based on whether the given value of the variable is considered to indicate high or low quality. For example, if a pH of 7.5 and biochemical oxygen demand (BOD) of 0 are considered most desirable, that those measurements might both be given sub-index values of 100, while a pH of 3 and BOD of 12gm^{-3} might be given values of 10. These sub-index values are subsequently combined or aggregated by some function to produce the final index. There are at least three methods of aggregation (Ott, 1978), an additive function, a multiplicative function and a minimum operator function.

Another approach to the sensible reduction of multivariate data characterizing the state of an estuarine water body was suggested by Seaton and Day, 1979. On analogy with the trophic state index generated for lakes by Brezonik and Shannon, 1971, they used factor analysis to reduce multiple measured values from many locations into patterns of common variance. They were able to find factors which separated the locations according to their apparent level of eutrophication as well as their salinity, with trophic state accounting for almost half of the variance.

A single variable indicator which might be used as an index of estuarine eutrophication has been suggested by Garber, 1991 and Garber and Boynton, 1991. They propose that annually-averaged depth integrated chlorophyll-a has a strong relationship with nutrient loading to a system. With data from five Chesapeake Bay subsystems and MERL mesocosms they have demonstrated a good correlation (r^2 = 0.81) with annual area-based total nitrogen (N) loading (in mg N/m^2/day) normalized by mean depth and hydraulic retention time.

Critique —
Performance: Information used to generate indices may be as local or as synoptic, as short or as long term and comprehensive as desired. A localized snap-shot of the system may be desirable to check response to a localized event; synoptic measurements over seasons or years may be necessary to determine the general system state. The primary problem with the performance of indices is eclipsing. That is, there is an inevitable reduction in the amount of information available to a manager when a multivariate description of a system is reduced to one or two descriptors. Eclipsing can conceal a degenerating situation until it becomes a problem rather than highlighting potential problems so that they can be dealt with. Indices tell little or nothing about the workings of the system, only something about the results of those workings.

Empirical Properties: There are no criteria for the confidence level or power of an index, and they are inherently extremely imprecise.

Applicability: Indices might readily be applied to tidal rivers, estuaries, lagoonal systems and forested coastlines. Indices do not elucidate processes nor indicate the levels of specific nutrients in a system. An index may give a coarse indication of the trophic state of an estuary and a time series of that index may suggest a trend in that state. An index constructed on measured aspects of some valued resource, such as a seagrass index, might indicate the vulnerability or decline of that resource.

Data Requirements: Most, if not all, of the variables used in index generation are standard water quality measurements which are likely to be part of a historical database, and likely to be part of an ongoing monitoring program. Therefore, their collection and analysis are likely to be familiar to personnel charged with the task. Calculation of an index can readily be programmed into a spreadsheet template that can be used by any competent technician.

Logistics and Costs: The measurements which are needed to generate an index might well be part of ongoing monitoring procedures. The types of calculations needed to generate a numerical index can be done with a hand calculator or spreadsheet. The use of factor analysis to develop a trophic state index (Seaton and Day, 1979) would require a microcomputer and some reasonably sophisticated statistical software.

Diagnostic Features: A low or declining minimum operator index (Smith, 1990) or trophic state index (Seaton and Day, 1979) might well provide the red flag to initiate special monitoring action.

Summary: The use of one or two descriptors to characterize a water body makes a coarse indication of the overall state of the system available to non-technicians. Inevitably, the reduction of several descriptors to one or a few will reduce the information available, making awareness of and response to specific problems or potential problems difficult.

Typical Values:

Description —
Measurements of one or more parameters made in a large number of estuaries, over a long period of time, make it possible to describe the extent to which a specific new measurement falls within a range of expected values. A measured concentration of 14.0 mg/l of dissolved oxygen, for example, may be unusual in a particular estuary, but compared to values from a number of nearby estuaries, the concentration may be understood as possible, but rare. Collateral information may reveal that such a high concentration is associated with supersaturation, hypoxia at night, or high chlorophyll a (phytoplankton pigment) concentrations.

Typical values are available for a number of estuarine parameters, and new comparisons can be assembled for unique data, as needed. The most straight-forward use of such values is the creation of a cumulative-percentile graph showing the probability of a given value's occurrence. The State of Florida, for example, has generated typical value curves for a number of water quality parameters. Curves are available for fresh waters and estuarine waters. The slope of such curves are diagnostic for each parameter, in Florida waters, provided that the sample size is very large.

Processes regulating parameter values are often subject to systematic, geographic variations which introduce error in the interpretation of a "typical" value. Sediment geochemistry is one example. Metals occur naturally in the sediments of Florida estuaries, but may also be present as a result of anthropogenic loads. In order to separate natural, background levels of metals in estuarine sediments from pollutants, the Florida Department of Environmental Protection developed a technique for normalizing metal concentrations by the concentration of aluminum. Aluminum acts as an indicator of how much metal load may be expected from native soils with a given clay mineralogy. By this technique, a new metal measurement may be determined to be typical of a polluted or unpolluted estuary, according to its ratio with aluminum.

Typical values of rarer elements, such as beryllium, can be evaluated through the use of their ratios with other elements. This technique is used most widely by geologists and geochemists, who employ isotopes of particular elements to age sediments, reconstruct historic climates and estuarine conditions, or label human pollutants.

Critique —
Performance: Typical values are good tools for range-finding and comparative assessments, but are inappropriate for analytical or process-based investigations. In their strongest applications, typical values are built from comparable estuaries and data sets. An example might be the surface, high-tide salinity of several west coastal riverine estuaries. Normalized typical values, as in the case of sedimentary metals, can be useful in discriminating natural from anthropogenic loadings at individual stations.

Empirical Properties: Typical value assessments are generally not amenable to statistical tests of any kind, although normalized data can be tested for variance from adjusted values. Percentile distributions are entirely descriptive.

Applicability: Typical values are broadly applicable to environmental parameters, including ecological attributes other than water or sediment quality.

Data Requirements: This method relies on one of three types of data. The first involves a large number of samples taken in a number of estuaries, over a variety of conditions. The second type involves a carefully constructed (filtered) set of data satisfying pre-determined criteria (surface measurement; high tides only, etc.). The third type is the data set comprised of data normalized to an independent standard, such as aluminum, in which case the sample size may be relatively small.

Logistics and Costs: Typical value assessments can be made using existing data, which reduces logistics and costs to the effort made in obtaining the needed information.

Diagnostic Features: This method is distinguished from others by providing a technique by which information from other similar or dissimilar estuaries can be assessed. It can be a part of the "Comparative" approach or used as a stand-alone method.

Summary: Typical values analysis is a relatively "soft" but often informative method for estuarine studies. Maximum benefit of the method obtains from either having a very large or precisely qualified data base, or normalizing data.

Dilution Curves:

Description —
Dilution curves, mixing diagrams, and mixing plots are all names for a graphical technique for the analysis of the behavior of constituent substances such as nutrients in estuarine waters. The information which can be obtained from the analysis is whether the substance is biologically or chemically reactive in the estuary and the approximate salinity range within the estuary in which any reaction occurs.

The basic theory of the method (Liss 1976) is that the concentration of a non-reactive or "conservative" substance is directly related to the relative proportions of the two end-member waters at the point of interest in the mixing region. Any deviation from that direct relationship will indicate, if negative, that the substance is being removed from the water, or, if positive, that the substance is being added to the water by some process. If the water at a point is half river water and half sea water, then any conservative substance in the mixture will be at a concentration exactly one-half the difference between the concentrations of that substance in the river and in the sea. Any substance which is not at such a concentration is then considered reactive or non-conservative.

Salt or chlorinity is considered completely conservative and is therefore used as the measure of the proportionality of the two end members at points in the reach of the estuary where mixing occurs. The river end-member is usually considered to have a salinity of zero and the sea water end-member is characterized by the measured value at the estuary mouth or the offshore point at which dilution is no longer of interest. If, for example, the measured sea water salinity is 35 parts per thousand, the salinity will be 17.5 parts per thousand where the proportions of the end-members are equal. Similarly, if nitrate is 14 microgram atoms per liter in the river and undetectable in the sea, we would expect it to be 7 microgram atoms per liter at the same point, if it were conservative. If, however, nitrate is at 2 microgram atoms per liter some process such as phytoplankton uptake is removing it from solution. By plotting nutrient measurements against concurrent salinity measurements, these differences are made apparent.

The method has also been limited to simple estuary systems of one major river source, i.e. a system with no tributaries. The potential problem lies in the interruption of the linear mixing process by the introduction of a new source of fresh water with potentially different nutrient concentrations.

McPherson and Miller, 1990, working in Charlotte Harbor, Florida, developed a new model of mixing which, although still dependent on a steady-state system, integrated the fresh water flow and nutrient concentrations from a number of tributary sources. The resulting graphs depict the necessarily non-linear conservative or "theoretical" behavior for the substance of interest if it were mixing non-reactively with the sea water end-member and compare it to the measured values of the substance. The conservative graphs are no longer linear, but deviation from conservative behavior based on the theory of water type proportions is readily apparent.

Mixing diagrams can be an effective diagnostic tool for detecting non-conservative behavior of substances in the tidal reach of an estuary and the complexity of the model can be varied to meet the requirements imposed by the character of the estuary, from a single source, steady state system to a dynamic, multiple source system.

Critique —

Performance: As with the box model, the picture of an estuary presented by dilution curves will represent the integrated behavior of the system over the time of sampling and averaging of the values used to build it. A one-time synoptic sampling scheme will represent the estuary at that time. Values averaged over a year will represent the net annual behavior. One time synoptic sampling is subject to confusion due to the potential for recent variation in end-member concentration or flow. Dynamic modeling of the mixing regime and the conservative dilution pattern requires sufficient data to characterize the system over a wide range of river flows.

Empirical Properties: Traditional dilution curves are an inherently imprecise tool for the coarse description of the behavior of nutrients in an estuary. Recent improvements including dynamic modeling of the mixing regime and the inclusion of multiple river sources have improved this picture, but not corrected it. The only measure of confidence available is the range of the measurements used to generate the values in the graph.

Applicability: In general dilution curves would be well suited for use in tidal river, estuarine, and lagoonal systems. It would be difficult to apply them to a forested coastline. The technique depends on knowledge of constituent concentration at the boundaries. There is no mechanism in the dilution curve technique to describe interactions between constituents such as nutrients and primary producers. However, if it becomes apparent that a nutrient is being lost in a particular salinity range, that would be an indication of productive uptake. Conversely, if it were apparent that a nutrient is being gained in a region, that would be indication of a source such as benthic regeneration or non-point or point source input.

Data Requirements: Basic dilution curves require only that salinity and nutrient levels be determined concurrently and synoptically throughout the region of interest. Dynamic modeling of the mixing regime and the conservative dilution pattern requires sufficient data to characterize the system over a wide range of river flows, as well as sufficient estuarine geometry to determine mixing coefficients at an adequate number of points through the region. Of course, multiple source dilution curves require synoptic determination of riverine input levels from all the sources.

Logistics and Costs: Depending on how synoptic they are, the measurements which are needed might well be part of ongoing monitoring procedures. Because the basic technique is essentially graphical, producing dilution curves can be accomplished by hand or with a microcomputer. The types of calculations needed for the dynamic mixing model or the multiple source model are also relatively straightforward and can be done with a microcomputer or calculator.

Diagnostic Features: Dilution curves can provide a valuable coarse description of system behavior. They can indicate whether an estuary as a whole or regions within the estuary are serving as sources, sinks or conduits for nutrients.

Summary: Although the technique is relatively imprecise, dilution curves can be an effective diagnostic tool for detecting non-conservative behavior of substances in an estuary. The method is fairly readily implemented, and the complexity of the model can be varied to meet the requirements imposed by the character of the estuary, from a single source, steady state system to a dynamic, multiple source system.

Indicator Species:

Description —

The theory underlying the use of species as indicators of environmental quality is that organisms are adapted to local ecological conditions as a result of natural selection (Pianka, 1974). In practice, the level of biological organization used for detecting environmental adaptation or maladaptation has ranged from the biochemical to the ecosystem. Cells, tissues, organs, single organisms, mating pairs, familial units, populations, species, co-evolved species pairs[1], and communities have all been used. Examples are given below:

[1] As in predator-prey pairs, competing species, and symbiotic interactions such as parasite-host or commensal species pairs.

Level	**Indicator**	**Response**	**Stressor**	**Reference**
Biochemical	Acetylcholinesterase	Decreased Activity	Pesticide	Fairbrother *et al.* 1989
Cellular	Starfish	Pigment loss	Emulsifiers	Perkins, 1968
Tissue	Bile Duct	Necrosis	Pollutants	May *et al.* 1987
Organ	Oyster Gonad Index	Decrease	Reduced Salinity	Butler, 1949
Organism	Benthic Fish	Asymmetry	Pesticide	Leary and Allendorf, 1989
Organism	Behavior in *Uca*	Loss of Motor Control	Dieldrin	Klein and Lincer, 1974
Population	Copepod	Population Decline	Pollution	Russell *et al.*, 1971
Community	Species Richness	Decline	Hyper-eutrophication	Santos and Simon, 1980

Any physical, chemical or biological parameter relevant to an organism in normal life has the potential of evoking a detectable biological change, at some level of organization, depending on the form and extent of its departure from natural conditions. Parameters outside an organism's natural experience can also act as stressors, as in the case of synthetic pesticides for which there are no natural analogs.

The literature on biological indicators is large. In addition to ecological and environmental sciences, the fields of toxicology, impact assessment, and resource management have also contributed extensively to the literature. For purposes of developing an Estero Bay Research Plan we concentrate on organismic, population and community-level indicators.

The range of available possibilities is illustrated by EMAP, or the EPA Environmental Monitoring and Assessment Program, which has evaluated a number of parameters as "ecological indicators", including biological indicators in near-coastal waters (Scott, 1990). High priority was given to benthic abundance, biomass, and species composition has been shown to integrate overall water quality and eutrophication. The extent and density of submerged aquatic vegetation was noted as a "research-level" indicator, as were (benthic) fish abundance and species composition; the presence of large indigenous bivalves (Taylor and Saloman, 1970), and gross pathology of fish. It is interesting to note that the EMAP near-coastal waters assessment discounted phytoplankton and zooplankton abundance and diversity because of the potential for high spatial and temporal variability. Other discounted indicators included shellfish growth and tissue contaminants, waterfowl and mammal abundance, and aquatic indicator species (those present or absent in polluted water).

Indicators of estuarine eutrophication exist at organismic and higher levels of biological organization:

Phytoplankton has long been the subject of study relative to nutrients. The EMAP review of indicators dismissed phytoplankton diversity and abundance as once-or-twice yearly descriptors, but did leave open the possible use of remotely sensed or directly measured pigment levels as indicators of "primary production imbalances." Strong correlations have already been demonstrated between mean annual chlorophyll a concentration in Chesapeake Bay and mean annual area-based loadings of nitrogen, and such relationships are being used to suggest management goals for Tampa Bay. Nutrient enrichment of estuaries may promote oxygen depletion by phytoplankton population flushes (blooms), or change phytoplankton community structure (as in promoting flagellates over diatoms). Indirect effects mediated by phytoplankton responses to nutrients include changes in secondary production among zooplankton, nekton, and benthic communities, and reduced light penetration to submerged aquatic vegetation.

Macroalgae are of interest as eutrophication indicators in two forms, as epiphytic growth on seagrass, and as proliferations of drift algae. Epiphytes are natural elements of seagrass communities but in excess can reduce light reaching seagrass leaves. Nutrient enrichment enhances epiphyte growth and may cause seagrass decline in estuaries. Attached (rhizophytic) and especially drift (planktonic) macroalgae have been used for decades as indicators of nutrient enrichment and sewage pollution. Algal tumours form near severe sewage pollution. Accumulations of single species such as *Ulva* or *Gracilaria* can reach nuisance proportions in estuaries of south Florida, and *Codium* has been reported covering offshore reefs.

Marine angiosperms, or submerged aquatic vegetation (SAV) have become useful indicators of estuarine eutrophication, particularly as mediated through loss of water transparency or epiphyte proliferation. Cases studies are available from Australia, Chesapeake Bay, and Tampa Bay. In Tampa Bay, sewage treatment and phosphate chemical plant discharges caused massive eutrophication of Hillsborough Bay, and SAV loss. Following abatement of nutrient loads, there has been a regrowth of rhizophytic algae and SAV. Such case studies utilized areal mapping and field surveys to depict temporal and spatial trends of seagrass cover in relation to point-sources or ambient water quality. Other parameters useful for SAV monitoring include chemical composition, standing crop, productivity, and reproduction.

Benthic faunal species and communities have documented responses to nutrient enrichment. A number of macroinvertebrate species of epibenthic or infaunal habit are recognized as indicators of polluted or healthy water. In Tampa Bay, moderate nutrient enrichment from a sewage treatment plant increased polychaete density, richness and biomass. Greater eutrophication leads to shifts from suspension feeders to deposit feeders. Severe eutrophication of Hillsborough Bay led to hypoxic conditions and annual defaunation. A number of analytical and statistical methods are available to identify benthic community responses to stress.

Critique —
Performance: Organisms have the ability to compensate for environmental changes within given ranges, without discernable effect. More extreme change results in chromic to acute effects and even more extreme change is lethal. Consequently, many uses of indicator species reflect conditions that have already progressed toward extremes. In other words, indicator species are likely to reveal pre-existing or worsening conditions (such as eutrophication) that could be discerned by other methods. Generally, indicator species are not well suited as early-warning systems, without special effort in measurement or observation. They are also not well-documented as indicators of the potential impact of future stresses. Phytoplankton has been used in a number of eutrophication studies. Time series of chlorophyll, biomass, or primary production rates are informative. Community structure, especially the ratio of diatoms to flagellates, also provides useful insight. Macroalgal species composition and biomass have been related to eutrophication in several estuaries. Epiphytic growth of algae on seagrasses is being used more to detect nutrient stress and, by the same token, direct measurements of seagrass biomass and growth are being correlated with nutrient input. There is some evidence that nutrient stress also promotes species replacement among seagrasses. Benthic infauna have been shown to respond in several ways to eutrophication. Examples include changes in biomass, density, diversity, and feeding type. Overall performance is very specific to the estuary in question and species selected for use. The method does not identify nutrient flux but can contribute to storage estimates if the proper measurements are made. With sufficient collateral data, the relationship of nutrients to primary or secondary production can be identified.

Empirical Properties: For the same reasons, indicator species may be ineffective measures of non-linear effects or threshold effects. Special care is needed to select the appropriate level of biological organization, and process, when there is reason to suspect or need to detect non-linearity, thresholds or, for that matter, lag effects. Benthic infauna, for example, may actually show enhanced densities or diversities in the presence of light to moderate nutrient enrichment, with infaunal declines resulting only from heavy nutrient load. Seagrass loss at depth (due to increased light availability) also exemplifies the complexity of non-linear and lag effects that are possible when dealing with estuarine eutrophication. Proper scaling in spatial and temporal dimensions is critical to the successful use of indicator species. A single, spatially intensive sampling of phytoplankton, for example, would be far less informative than a similar effort for benthic infauna. On the other hand, a lengthy time-series for algae (phytoplankton or macrophytes) would be very helpful in detecting eutrophication trends in localized areas.

Applicability : Indicator species are applicable in any habitable estuary, although the preferred mix of particular species or processes needs to be tailored for the biogeographic setting, type of estuary, and nature of stresses that exist there. It is not likely that a single suite of indicator species other than phytoplankton will be appropriate across an area of large regional diversity, such as southern Florida. The main reasons for this are circulation, salinity, and sediment chemistry differences.

Data Requirements: Types of data required for indicator species studies may range from biochemical to ecosystem levels, as described earlier. In common use are distributional data (location, presence, absence, etc.); distribution trends; condition (density, species richness, growth rate, standing crop, etc.), and behavior. Data collected over time are preferable to "snap-shot" data sets, although sampling frequency needs to be selected with attention to the frequency of such important parameters as tide, inflows, temperature extremes, etc.. Collateral data are needed to interpret indicator species results. For eutrophication studies, the concentration of dissolved and particulate nutrients will be helpful, but the value of these data depends on turnover and storage rates of the estuary, and the type of indicator species.

Logistics and Costs: The complexity of sampling for phytoplankton, algae, seagrasses or infauna is generally lower than the complexity of sample processing. Exceptions to this generalization are rate measurements, such as in situ phytoplankton productivity or benthic respiration. Community surveys require taxonomic expertise and sample processing times are higher than for most biomass samples. Aerial (and some other remote) data acquisition systems offer speed but must be supported by collateral data.

Diagnostic Features: An important feature of indicator species is that the method can simultaneously monitor eutrophication trends and the status of an economically or ecologically important species. The method resembles the VEC method in this respect, except that the VEC method tends to be more analytical and indicator species tend to be more descriptive.

Summary: Indicator species present a large palette of choices from which elements of a eutrophication monitoring program may be selected. Their use has the advantage of dealing directly with ecological resources of value. A major limitation in their use is the dependency of the method upon a sufficient amount of natural history data for the particular species. Collateral data requirements range from small to large. Overall, the method is highly supportive of decision-making in resource management arenas.

Valued Ecosystem Component Analysis:

Description —

The Valued Ecosystem Component (VEC) approach is the general name that can be given to a method developed by the Environmental Protection Agency as a model to guide the design of monitoring programs in the National Estuary Program (NEP). The VEC method makes statistical, correlative statements describing the connection(s) believed to occur between stressors and ecosystem components of value (Environmental Protection Agency, 1987). Biota may be of economic value, as in the cases of commercial or recreational fishery species, or of ecological value, as in the cases of keystone species, indicator species, or endangered species. EPA envisioned that stressors evaluated by the VEC method would be typical estuarine problems.

In theory, step-wise, causal links are identified working from a valued ecosystem component to a stressor. The process of identifying these links can be based upon hypothesis-testing (by collecting new data) or it can be based upon analysis of existing data. The method admits that multiple stressors probably affect a particular VEC, and it relies on local expertise to select specific stressors for evaluation. As causal links between VEC and stressor are identified, the collateral effects of stressors extraneous to the analysis are ignored. In ideal form, changes in the distribution, amount, or condition of a VEC that can be attributed uniquely to a single stressor are described.

The method is intended to work for the special case of nutrient stress in estuarine environments. It differs fundamentally from traditional methods of determining necessary nutrient limits by beginning with the VEC rather than the nutrient source. Traditional methods such as technology based or water quality based effluent limitation studies[2] begin with precise estimates of nutrient load, proceed to less-precise estimates of storage and transport, and end with often-ambiguous conclusions about biological effect. In contrast, the VEC method can be regarded as a "resource-based" effluent limitation in which the ultimate biological impacts of a stressor act to drive necessary load reductions.

For example, sea grasses are considered a valued estuarine ecosystem component (Scott, 1990). Sea grass decline is widespread in Florida estuaries and a number of causes have been documented or suspected (Gulf of Mexico Program, 1991). Some involve nutrients and nutrient impacts to sea grasses are probably made manifest by more than one pathway. One pathway related to light is listed below.

Nutrient Load ----> Phytoplankton Bloom ----> Increased Chlorophyll ----> Increased Scattering and Absorption ---> Decreased Transparency ---> Sea Grass Loss

In this case, the VEC method would proceed as follows. First, patterns and trends in the decline of sea grass cover, density, or standing crop are related to patterns and trends in transparency. Then, characteristics of transparency are identified, concentrating on the relative contributions of scattering and absorption by color, inorganic and organic particulate matter, and pigment (phytoplankton). Next, the relation of pigment concentration to the number, kind and size of cells are identified. Finally, these bloom characteristics are related to the quantity, timing, and transport of specific nutrient loads. Components of this approach as it applies to sea grasses in Tampa Bay, Florida may be found in Proceedings of the Tampa Bay Symposia.

[2] Also called waste-load allocations in some regulatory programs.

As noted earlier, such analyses may be driven either by existing data (in data-rich estuaries) or by new data collected specifically for an estuary, stressor, or VEC. Data collection involves the coordinated measurement of specific parameters listed in the pathway from nutrients to seagrasses. Results are not represented as statistically significant, or as being exclusive of alternate explanations: the parameter changes could be related to more fundamental causes, or the changes could be mere coincidences. According to EPA, the VEC method relies on a preponderance of evidence in support of a particular impact pathway rather than scientific proof.

Critique —
Performance: VEC is basically untested as a formal method so performance data are unavailable. As posited by EPA, the method was meant to guide design of NEP characterization studies. It embodies elements of successful process-related studies conducted elsewhere. The method is not best suited for measuring nutrient flux or storage per se, compared to others, but should do well relating nutrients or detritus to primary and secondary productivity.

Empirical Properties: Because links between stressors and resources are not definitely known, as in the case of a hydrodynamic model, accuracy and representativeness of measurement tend to be more important than precision. Results would not be represented as statistically significant, or as being exclusive of alternate explanations: the parameter changes could be related to more fundamental causes, or the changes could be mere coincidences. The most robust statistical demonstrations would be regressions, correlations, or analyses of variance, for which the respective assumptions would have to be met. Non-linear relationships may be expected but are resolvable.
Applicability: EPA's guidance to NEP projects was based on pollutant stressors, either point or non-point, acting upon valued ecosystem components. Flexibility exists for local estuary programs to identify the pertinent stressors and VEC. In theory, the method would be applicable to non-pollutant stresses (over harvesting, for example) so long as an explicit series of causal links to a VEC can be postulated. The method would not work well where signal-to-noise ratios were lower than detectable by statistics mentioned above.

Data Requirements: In some instances there may already exist sufficient data for an estuary, on the relevant parameters. In general, the period of record necessary for such monitoring data to be effective is a function of the simultaneity, spatial proximity, and completeness of the independent sets. EPA intended that historical and new data be used to drive VEC assessments, with the method guiding decisions about new data collection programs. Where new data are collected, temporal and spatial intensity may be able to replace long-term data. In this case, care is needed to collect useful information on stressor and VEC co-variation.

Logistics and Cost: Analyses based entirely upon historical data are relatively uncomplicated, logistically, and do not entail very high costs. Analyses based upon new data can become logistically complex, especially if attempted in a relatively short (under 3 year) time frame. The reason for this is the simultaneity required for sampling and measurement of multiple links in the causal chain posited for the system, and appropriate scaling. EPA considered VEC studies based on a blend of historical and new data to be achievable within the time and budget constraints of the National Estuary Program. The method could be less expensive in data-rich systems.

Diagnostic Features: This method is synoptic in that it can evaluate a series of causes and effects that cross physical, chemical, and biological processes. However, the method is limited as a tool by which intrinsic features of an estuary may be discovered because it is designed to evaluate a causal relationship suggested a priori, and discoveries would be serendipitous. One noteworthy feature of this method is its ability to employ historic data as well as useful data from comparable systems.

Summary: The valued ecosystem component method represents an explicit form of ecological process-modeling in which causal links are evaluated beginning with the affected resource and working back toward stressors. Variations of the method are underway in NEP estuaries. Both existing and new data are employed. Overall, the method has the potential to improve decisions involving stressor controls or VEC management.

Mass-balance Models:

Description —
In general terms, mass balance refers to the method of characterizing and analyzing storages and transfers of a material (usually a specific element) by accounting for it's mass in a natural system, based on the fact that mass is conserved. In the case of N or P nutrient cycles, a complete mass balance includes all storages, transformations, and transfers (including import and export) of mass for an ecosystem. Thus a complete N and P mass balance would completely describe the system in regard to these elements and would form an ecological model.

Because mass is conserved, that is neither created or destroyed, all of the element in question that exists within a defined system can be accounted for by keeping track of its partitioning into compartments within the system (e.g. benthic, dissolved, suspended particulate) and through its transformations from one form to another (e.g. nitrification, denitrification, organic incorporation) from its entry into to its loss from the system at the boundaries. However, natural systems are usually too complex to be described completely, so some degree of simplification or abstraction is necessary. This simplification may be in terms of an ecosystem model in which certain components are lumped into general categories, or it may consist of applying a mass balance approach to a limited subset of the system's components. One such subset that can be particularly illuminating with regard to nutrient dynamics in aquatic systems is the subset of transfers of mass across the system boundaries (import and export). Any attempt to model a system using any of these approaches can be considered a mass-balance model.

A number of mass-balance modeling approaches in estuarine ecosystems have been implemented, but by themselves cannot be used to predict the effects of nutrient additions on the entire system. Conversely, ecosystem modeling efforts like that in Narragansett Bay have worked, but only a very limited portion of the model's functional relationships involved nutrient mass balances.

It is has proven very difficult to accurately evaluate even mass balances across estuarine systems boundaries. For example, numerous authors have pointed out that the exchanges of materials between marshes and coastal waters was uncertain. Kjerfve *et al*. (1981 and 1982) showed that much of the difficulty in developing accurate mass balances and import/export budgets for estuarine systems had to do with the difficulty in accurately sampling fluxes.

Critique —
Performance: Because so few mass-balance modeling approaches have been carried out to the degree necessary for them to be useful for management purposes, they have to be considered relatively untested and unproven in this regard. Also it is important to understand that performance of the modeling aspect should be evaluated separately from the characterization and quantification of processes important to storages and transfers of nutrient masses. Performance of various modeling approaches is extremely variable.

Empirical Properties: The types of information that are necessarily obtained in mass-balance modeling can be very precise and accurate. However, this type of information is not generally amenable to statistical treatments. The accuracy/precision of the modeling aspect, as with its performance, depends on the types of modeling employed. Overall, mass-balance modeling, because of its complexity, is not likely to provide the kinds of information that can identify or predict small changes. Instead, it should be considered to in most cases provide guiding principals (e.g., determination of limiting nutrients for various components) that would be useful to resource managers.

Applicability: Because this approach involves direct analysis and quantification of nutrient storages, pathways, and processes, it is applicable to almost any natural system. However, because ecological components and processes may function differently in different conditions or different systems, mass balance modeling approaches may not be directly transferable from one system to another -- modification or refinement may be required for each system or subsystem. Additionally, basic scientific understanding of nutrient cycling processes is not always available. The extensive literature on nutrients in estuaries is largely derived from temperate systems, and processes and functioning in subtropical/tropical systems like those found in south Florida may be different and may require basic research for accurate understanding.

Data Requirements: Mass-balance modeling approaches have high data requirements. Even for the simpler case of mass balances across estuarine system boundaries, an extensive literature has developed showing the high degree of data requirements. Conceptual models or models of key components, not only have requirements for extensive data, but also can require basic research into processes and relationships.

Logistics and Cost: The resource demands of mass-balance approaches are comparatively high. These demands include a requirement for extensive technical expertise, as well as requirements for extensive data collection. Additionally, the modeling aspect can range from moderate (e.g., for conceptual/pedagogic modeling) to extremely great (e.g., for predictive simulation modeling). However, after initial investment in development of mass-balance models, the long-term costs of this approach may be no more than other approaches.

Diagnostic Features: Mass-balance approaches, because they involve elucidation of fundamental processes and relationships, provide perhaps the best information on which to evaluate and manage an estuary. The main problem, however, is the acquisition of such information.

Summary: Mass-balance modeling has generally been used to understand processes and functioning, rather than to assess and manage systems. Due to the complexity and high degree of technical requirements of such approaches, mass balances cannot be expected to provide information that is immediately useful for management purposes. Since mass-balance modeling approaches provide improved scientific understanding of estuarine systems, there is great potential for mass-balance models of key components of estuarine systems to improve research managers long-term abilities to protect and manage estuarine ecosystems.

Box Models:

Description —
Box models are a simplified water quality modeling technique for the analysis and prediction of conservative or non-conservative dilution and distribution of constituents, such as nutrients, in an estuarine system. Regional constituent sources and sinks can be determined and rates of uptake or input can be estimated. The model can be one, two or three dimensional, providing the ability to discriminate benthic and photic zone sources and sinks and lateral variations in multi-channeled systems. Box models have primarily been limited to one or two dimensions as described by Officer, 1980. But recently the method has been extended to a full three dimensional system. Box models have been used successfully to characterize the distribution and exchange of nutrients, sediments, contaminants, and algae.

In a box model the estuary is divided into a series of boxes or segments which contain water of relatively constant properties such as salinity. Each box can have one or two water layers. The model is time independent, that is, it assumes a steady state or equilibrium balance between the inflow of fresher water from riverine sources and the input of salt and tidal mixing energy from the sea. Equations characterizing the conservation of water and salt are solved for each box directly from observed sets of salinity measurements and river flow. Values for all observed quantities are averaged over the volume of each segment or box and over tidal cycles. Because these equations are conservative and at equilibrium rather than dynamic, there are exact solutions for each estuary and measurement set. This eliminates the need to make calibration trials to tune the model. The solutions to these equations provide exchange coefficients which can then be used to describe the exchange rates of any conservative substance between boxes. These exchange coefficients include flux due to diffusive processes as well as to turbulent mixing. Any departure of a the concentration of a substance from that predicted using those exchange rates indicates non-conservative behavior, i.e. sources or sinks such as benthic nutrient regeneration or phytoplankton uptake.

Using exchange coefficients and flux information, a constituent balance equation can be written for each box. This leads to a system of linear equations for the whole model, of matrix form.

In systems which can be sampled over a sufficiently consistent regime, box models provide a valuable first order estimation of system behavior.

Critique —
Performance: The picture of an estuary presented by a box model will represent the integrated behavior of the system over the time of sampling and averaging of the values used to build it. A one-time synoptic sampling scheme will represent the estuary at that time. Values averaged over a year will represent the net annual behavior.

Empirical Properties: The precision of box model estimates rests entirely on the sizes of the boxes or segments which are chosen and the precision of the data. There is no statistical measure of confidence which can be given to these estimates, although the model could be solved with representative levels of input over the ranges that normally occur. This would amount to a form of sensitivity testing of the model.

Applicability: In general the box model would be well suited for use in tidal river, estuarine, and lagoonal systems. Because the direction and magnitude of flow must be known, it would be difficult to apply to a relatively open forested coastline. The model depends on knowledge of constituent concentration at the boundaries, but it will estimate the average net effect of sources (e.g. runoff) and sinks (e.g. sediment deposition or primary production) within each segment. There is no mechanism in the box model to describe interactions between constituents such as nutrients and primary producers. However, if a segment is identified as a nutrient sink it may be inferred that production there is sufficient to take up the nutrient at that rate.

Data Requirements: For one dimensional or vertically segmented box models, the river inflow is used as the net flow through any segment. In laterally segmented models, however, the direction and volume of average flow between laterally adjacent segments must be known. Values for all observed constituent levels are averaged over the volume of each segment or box and over tidal cycles. It is only necessary to have values determined in a representative variety of circumstances so that the average state of the whole segment is characterized. Estuary cross sections at the segment interfaces are necessary for the calculation of mixing coefficients.

Logistics and Costs: Depending on how comprehensive they are, the measurements which are needed might well be part of ongoing monitoring procedures. On the other hand, Doering *et al.*, 1990 conducted six synoptic samplings of nutrient concentrations in the estuary and point source inputs over the course of about a year, collecting at least two samples within each estuary segment. There is no need to make specific measurements to calibrate or validate the model. Because box models are essentially a set of simultaneous linear equations, they can readily be solved on a microcomputer or programmable hand calculator.

Diagnostic Features: Box models can provide a valuable first order estimation of system behavior. They can indicate whether an estuary as a whole or regions within the estuary are serving as sources, sinks or conduits for nutrients. If a new source of nutrient load is anticipated at some point in the estuary, a box model can be used to estimate the resulting distribution of that substance.

Summary: Box models have inherent limitations. They are severe simplifications of actual hydrodynamic processes, including no temporal variation. They are extremely sensitive to input salinity and river flow which can distort apparent constituent distribution and reactivity. In addition, the fate of constituents which may undergo a variety of reactions may be difficult to diagnose. However, in systems which can be sampled over a sufficiently consistent regime, where either change does not occur within the hydrodynamic residence time or the sampling period is long enough to encompass and average normal variation, box models provide a valuable first order estimation of system behavior.

Hydrodynamic and Water Quality Models:

Description —
Hydrodynamic models are mathematical representations of water bodies not unlike box models, insofar as both use the conservation of mass as their underlying principle. Hydrodynamic models differ from box models by not requiring steady-state conditions. They instead use estimates of storage and flux to represent dynamical conditions through a series of time-steps, within which the storages and fluxes in and between model cells (or boxes) are re-computed.

Water bodies such as estuaries are divided into cells using either fixed or curvilinear grids. Input data to hydrodynamic models include boundary conditions (tide range, freshwater input, land, etc.), depths, bottom types or coefficients of bottom roughness, and initial density or salinity conditions. The models compute the movement of water and conservative substances between cells as tides and fresh water inflows vary. Models simulate effects on water motion of density differences in water masses; bottom features such as channels and sills, and astronomical factors such as Coriolis forces. Still more sophisticated models account for meteorological conditions. Outputs of models include water surface elevation, circulation of water (current speed and direction) and concentrations of conservative constituents such as salt. Water quality models add extra computations to each time-step to account for variations in non-conservative constituents such as oxygen or chlorophyll, following simple to complex rules.

Models may operate in one, two, or three computational dimensions. A well-mixed, shallow river may be modeled in one dimension. A density-stratified river, or a broad, well-mixed estuary, may be modeled in two dimensions (horizontally in the latter case; vertically in the former). A density-stratified estuary such as upper Charlotte Harbor would be modeled in three dimensions.
Hydrodynamic models have been employed to describe patterns of circulation in estuaries. Estimates of flushing times can be calculated from model outputs. Models describe such circulation features as gyres, fronts, eddies, and seiches. Models can also be used to describe surface conditions such as wave climates. Circulation models have been applied to problems concerning the effect of causeway, channel, and island construction, or removal. Models have been used to identify areas of poor flushing, and optimal restoration strategies. By the same token, models have been used to depict long term patterns of temperature, salinity, and sediment distributions in estuaries.

In the past 16 years hydrodynamic models have also been used to describe or predict distributions of phytoplankton, zooplankton, ichthyoplankton, particulate pollutants, dissolved pollutants, and numerous other constituents of estuaries. More recently, fully capable models have been created to simulate such ephemeral properties as hypoxia, light climate, larval settlement zones, and even productivity of submerged aquatic vegetation. Models have been used to assess the potential ecological effects of large public works projects such as bridges, navigation channels, flood control structures, or habitat restoration efforts.

Many models are proprietary, meaning that sponsors or users of the model output have little or no access to the source code. All new uses or applications of a proprietary model are paid for as extra costs.

Critique —
Performance: Hydrodynamic models are calibrated and verified through the use of independent data sets. Goodness of fit between model outputs and measured data is often very high for stage (water level) and currents; decays with conservative constituents, especially in strongly stratified environments, and may be quite poor for non-conservative constituents. Acceptability of outputs is normally not decided on the basis of pre-determined criteria but rather on the expert opinion of the modeler, in consultation with the project sponsor and eventual user of model products. Considerable effort is made to make a model represent the natural system well. A common difficulty for resource managers is that standard model outputs often fail to present information on stage, currents, flushing, or other physico-chemical attributes in meaningful ways. Some models that succeed in hydrological terms turn out to be uninformative for researchers or managers, without considerable extra effort and expense. Prospective users of models are cautioned to participate fully in early decisions regarding the model's geographic and temporal scales, range of natural conditions to be considered, formats of output, and ability to test scenarios.

Empirical Properties: Hydrodynamic models are deterministic representations of nature but, once calibrated and verified, are not one-to-one simulations of actually occurring conditions in nature. Outputs are not normally amenable to statistical analysis.

Applicability: As described above, hydrodynamic, salinity, and water quality models are broadly applicable to a number of scientific and resource management problems. Their use is very shallow waters is not widespread, especially where the effects of wind are common and strong. Models handle intertidal areas of estuaries poorly, or not at all.

Data Requirements: Models require a bathymetric chart and estimates of bottom type; definition of land-water margins; tide records, and estimates of freshwater inflow. As the model is developed and tested, real-time records of water level, current speed and direction, and salinity become increasingly important.

Logistics and Costs: Such data are usually collected in major modeling efforts by continuous, in-situ sensors and data loggers, the deployment and maintenance of which can be difficult and expensive. In unstudied waters a year or more of start-up data may be required. The costs of data collection and modeling are lowest for one-dimensional models. Fully developed three-dimensional models that include water quality and other non-conservative or ecological conditions may cost a million dollars or more, depending on the size of the estuary, scaling decisions, and number of scenarios tested.

Diagnostic Features: Hydrodynamic models account for underlying physical processes of estuaries and illuminate basic currents, circulation, and flushing characteristics of the system. Salinity can be modeled with good fits to measured data, less so in highly stratified estuaries. Models with ecosystem processes are in use and enable scientists and managers to evaluate system-level responses to natural and anthropogenic changes, but far more work is needed (from ecologists) before modelers will achieve ecological predictability.

Summary: Hydrodynamic models are powerful and often essential tools in estuarine science and resource management. Even the strongest aspects of modeling (water level, circulation, flushing, salinity) are difficult to apply in very shallow systems, especially those dominated by intertidal areas. Models are extremely expensive, often proprietary, and sometimes finished with little final application to important management issues.

Bioassays And Mesocosms:

Description —
Bioassays and mesocosms are controlled experiments in which biota are exposed to environmental conditions ranging in their similarity to nature. The most simplified and controlled experiments are bioassays and the most complex are mesocosms. Bioassays tend to involve carefully selected, often cultured, specimens of a single species to experimental environments in which only one or a few parameters are allowed to vary. Traditionally, bioassays were performed under laboratory conditions and lasted for hours, days, or weeks. Examples of bioassays are the growth responses of phytoplankton cultures to infusions of nutrients, or the mortality of shrimp larvae after exposure to a pesticide. Driven mostly by the science of environmental toxicology, bioassays are now being conducted in open systems that more closely resemble natural conditions. Some bioassays are actually performed in the field while others use wild-caught specimens, or groups of species.

Mesocosms seek to reproduce more environmental variability than bioassays, while retaining control over specific parameters of interest. Mesocosms may be created in the lab through the use of standing waters, re-circulated waters, or once-through seawater. Mesocosm environments may be indoors or outdoors, or in-situ (actually in the field). An estuarine mesocosm may be a pelagic photosynthesis chamber, benthic respiration chamber, or intertidal enclosure of particular species. Fouling plates are mesocosm experiments. Large to very large volumes of oceanic water have also been enclosed at sea. Mesocosms have been used to examine productivity, grazer effects, predator-prey interactions, and the effects of changing numerous variables in population and community ecology. Depending on the nature of the investigation, mesocosm experiments may run for weeks, months, or years.

Bioassays tend to have stricter quality assurance requirements than mesocosms, because the experiment of interest in a bioassay is being conducted under highly simplified and controlled conditions. Large replication of bioassays, for example, is more commonplace than large replication of mesocosms, especially mesocosms conducted in open waters. Precision is emphasized in bioassays whereas accuracy is important to mesocosms. Both require a deep working knowledge of the organisms and environmental variables used in the experiments.

The range of controlled-exposure environments represented by bioassays and mesocosms reflects an experimental approach to understand the simplified effects of particularly-defined conditions upon plants or animals of interest. These experiments are powerful tools for the testing of hypotheses regarding processes regulating the distribution, abundance, or condition of organisms. When used in concert with studies working at different scales of space and time, bioassays and mesocosms offer scientists a considerable ability to discover the basis for important ecological processes.

Critique —

Performance: Bioassays perform very well insofar as determining the isolated effects of single-parameter variation are concerned, though their results can be difficult to extrapolate to real-world conditions. Considerable control is required over experimental organisms and conditions, often creating experiments that are highly precise but inaccurate. Mesocosms, on the other hand, are often complicated by unexpected or uncontrolled changes to the initial conditions of the experiment. This has fortuitously led to unexpected discoveries but more often requires the experiment to be repeated.

Empirical Properties: Bioassays produce data useful in the calculation of rates important in population models. Mesocosms produce data important for primary and secondary productivity, and population to community-level processes. While the importance of replication is known for bioassays, more information is needed on the effect of replication on mesocosm results.

Applicability: The range of experiments encompassed by bioassays and mesocosms are broadly applicable to a number of autecological (single-species) problems, as well as problems concerning species pairs (prey-predator; host-parasite, etc.) and communities of organisms. They are best used as part of multi-level and scale investigations.

Data Requirements: Data requirements depend largely on the nature of the experiment, but bioassays and mesocosms tend to produce relatively small data sets which can be analyzed by hand or with commercially available applications.

Logistics and Costs: Bioassays are logistically simple to complex, depending largely on the source of biota and degree of desired control over particular parameters. Wild-caught organisms are often easier to provide than cultured species. Experiments involving changes to common parameters (temperature, salinity, etc.) are easier and less expensive than bioassays involving contaminants in very low concentrations, or unusual parameters (such as pressure). Land-based mesocosms have large startup costs for facilities, but once facilities are available, maintenance and operation costs can be minor. Mesocosm experiments conducted in the field pose all the logistic and cost problems of other field studies.

Diagnostic Features: These methods are formal experiments and as such probe more deeply into natural ecological processes than simple descriptive science. The methods allow for hypothesis testing through the use of statistical analysis intended for rigorous experimental designs, which descriptive field studies rarely enjoy.

Summary: Bioassays and mesocosm studies are powerful tools in estuarine ecology, if conducted by scientists with a thorough working knowledge of the species and environments involved. These tools have been under-utilized in estuarine settings but offer much promise for problems of interest to resource managers.

Whole-system Manipulation:

Description —
Any change, intentional or otherwise, to an estuarine system might be considered to be a whole-system manipulation. However, in order for such a manipulation to be useful in understanding or predicting the results of the change, standard experimental approaches demand that certain conditions must be met. The change must be known, quantified and understood. Other variables must be controlled, or at least documented well enough that their independent effects can be recognized. Likewise, the interaction of uncontrolled effects on the manipulation must be known. The effects of the system manipulation must be carefully determined, and a control, initial or recovery condition, against which these effects can be compared, is necessary. It is therefore obvious that such conditions are rarely attained for open, complex, and continually changing systems like estuaries.

Because of these constraints, the whole-system manipulation approach would not usually be considered as viable method for assessing the impacts of water management or nutrients on estuaries. On the other hand, Florida water management districts are in the very unusual position of being able to meet these conditions through their roles of monitoring, managing and implementing changes to estuarine systems. Regulation of freshwater inflow, for example, affects nutrient loading to an estuary and the impacts of loads associated with particular inflow regimes could be evaluated experimentally.

Recently, there has been substantial scientific interest in the theory and value of whole-system experiments . These theoretical treatments range from sophistication and application of traditional experimental design to "active adaptation" in which ecosystem response assessed by alternative models that are proposed and evaluated within the context of management experiments (Walters and Holling, 1990).

Whole-system manipulation has also been a tool in lake ecology. However, almost all of the whole-system studies have consisted of experiments directed toward understanding ecological processes and functioning rather than applied management. Whole-system experiments have not been widely used for management applications. Perhaps the best examples of this approach are those in which experimental lakes have been manipulated with regard to factors such as acidification and nutrient additions. Comparable direct "bottom-up" manipulations of estuaries have not been performed. However, "top-down" manipulation of ecosystems, in which higher trophic levels are managed, has been developed for addressing eutrophication of estuaries (Leeis, *et al*., 1989).

Local examples of whole system manipulations involving nutrients and estuaries can be found in Florida. In Tampa Bay, reductions in nutrient loading that resulted from improvements to the region's phosphate chemical industry, and to the City of Tampa's wastewater treatment plant were found to result in lower dissolved nutrient concentrations in bay water, fewer incidents of nuisance algae, and seagrass recovery. Although technically not conducted as a temporary or reversible experiment, careful monitoring of this ecosystem-level change in nutrient inputs resulted in data meeting many of the criteria listed earlier. It is reasonable to conclude, therefore, that whole system nutrient manipulations in estuarine systems are possible either as an indirect result of inflow regulation or as a direct result of changes in nutrient load.

Critique —
Performance: Whole system manipulation has been a very powerful tool for understanding responses of relatively closed systems like lakes to nutrient additions or to decreased nutrient inputs. There is insufficient information to presently determine the performance of whole-system manipulation of highly open systems like estuaries.

Empirical Properties: In those closed systems for which extensive whole-system manipulations have been conducted, extremely precise and accurate information on the effects of nutrient increases or decreases have been obtained (Schindler *et al*., 1987). Because counter-manipulations (nutrient increase and nutrient decrease) can be performed, results can be considered to give predictive insight into potential system responses to nutrient changes. The degree to which manipulation of open-system estuaries would provide similar results is uncertain. This is particularly true with regard to long-term chronic effects, which would require that the system be manipulated, controlled and monitored for protracted periods. For most South Florida estuaries, population increases and attendant anthropogenic impacts might make long-term impact studies impossible.

Applicability: At first glance, it would appear that whole system manipulation would have little application to South Florida estuaries that are extremely open with respect to inputs and exports of nutrients, fresh water and other constituents. However, SFWMD through its mandate to monitor and manage estuaries and many of the inputs, may have the control and monitoring capabilities necessary for whole-system manipulation experiments. For example, any major alteration to nutrient inputs arising from water management decisions could be incorporated into an "experimental design" for a whole-system manipulation. However, not all South Florida estuaries could be easily manipulated, so the applicability of this approach might be considered limited. Nevertheless, cases where nutrient perturbations to important systems are unavoidable could be treated as a whole-system manipulation (as was done for Lake Washington by Edmondson and Lehman, 1981) and thus provide valuable information needed to manage the system.

Data Requirements: Data requirements of whole-system manipulation approaches can be expected to be intense. However, such requirements usually would be short-term, and therefore the overall data requirements of this approach could be modest compared to many other approaches.

Logistics and Cost: The main logistical consideration for this approach is the ability to control the manipulated parameter and to control and monitor other parameters and conditions in the system. The cost would be dependent upon the approaches used to characterize and quantify the effects of the manipulation.

Diagnostic Features: The diagnostic capabilities of this method is dependent on the approach used to characterize and quantify the effects of the manipulation.

Summary: Whole-system manipulation is a novel untested way of assessing the effects of nutrient changes on an estuarine system. This is not an independent approach because one of the other approaches would have to be adopted as the approach by which the effects of the manipulation are evaluated. By viewing any significant change (planned or otherwise) in nutrient input as a whole-system manipulation, valuable information could be obtained.

Comparative Studies:

Description —
Comparative estuarine studies is a broad term which encompasses at least two quite different enterprises. One is the organized study of two to a few estuaries which have some features in common such as general geography and geomorphology with the aim of elucidating differences which presumably derive from the varying level of some perturbation, usually human impact. Another type of comparative study is a survey of available information concerning certain characteristics of many estuaries of a variety of geographies or geomorphologies in the effort to derive conclusions about estuarine behavior which are common throughout the group.

An example of the first type is the work of Browder and colleagues in Faka Union Bay, Florida. In this study, species abundances and salinity distributions in Faka Union Bay and the adjacent estuary on each side, Fakahatchee Bay and Pumpkin Bay, were compared. The water in Faka Union Bay was found to be less saline than that in the other bays due to a canal system discharging there. A relative decrease in species abundances was related to this reduction in salinity and specifically related to a decrease in the areal extent of optimal salinity bands within the estuary. If unimpacted systems are available for study, this type of comparison can be extremely effective in pinpointing the causes and effects of specific problems.

Examples of the second type of comparative study are several. Deegan *et al*., 1986 looked at data from estuaries around the Gulf of Mexico to investigate the relationship between physical factors and the occurrence of vegetation and fisheries harvest. They found that the amount of emergent vegetation is related to the coastal land slope, the length of coastline occupied by the estuary and rainfall, but not to river flow. On the other hand, fisheries harvest per unit open water area in the southern Gulf was strongly related to river discharge (r=0.98).

In a comparison of 6 Texas estuaries, Armstrong, 1982 used geomorphic, hydrologic, hydrographic, nutrient loading and commercial fisheries harvest indices as bases. The estuaries were found to be fairly similar geomorphically, but showed a variety of biological responses relating fin and shellfish populations and harvests to the salinity regime in the estuary as well as the areal loading rates of nutrients.

Through reviewing data from 63 widely divergent estuaries, Boynton *et al*., 1982, were able to develop interesting physical as well as biological conclusions. They found the estuaries could be statistically classified by a step-wise discriminant analysis which indicated that salinity, extinction coefficient, flushing rate and latitude were important descriptive characteristics. Recently this group has extended the work and found what may become a predictive model of estuarine eutrophication that relates areal nitrogen loading to annually-averaged depth-integrated chlorophyll-a.

Quinn *et al*., 1989, were concerned to estimate the relative susceptibility of estuaries of the U.S. Gulf of Mexico to the retention and concentration of nutrients as well as their current status in relation to nutrient discharge. In order to assess relative susceptibility to eutrophication they developed a measure called the dissolved concentration potential (DCP). The DCP characterizes the effect of flushing and estuarine dilution on the load of a dissolved pollutant based on the fresh water fraction of the estuarine volume and the rate of freshwater inflow. Florida Gulf estuaries were found to encompass a broad range of susceptibilities with the Suwannee River the lowest and Tampa Bay the highest. Such comparisons of the susceptibilities of the estuaries in a region to eutrophication simply based on physical factors could be valuable in management decisions when cost-benefit calculations are made. Resources could be allocated to estuaries where the most response could be expected.

Critique —
Performance: Depending on the type and purpose, comparative studies can be responsive in the short term or require many years of effort to complete. A comparative study of estuaries of south Florida might be accomplished quite readily using historical data available to the District. A well designed comparative study of a particular problem, such as fresh water wetlands loss, in a pair of estuaries in the District might require several years for a sensitive elucidation of the processes involved and the consequences implied.

Empirical Properties: Specific comparative studies provide the potential for statistical tests of differences between the systems, with the confidence and power that implies. Global or regional comparative studies provide many degrees of freedom for tests of relationships common to all the estuaries and for determining patterns of behavior common to groups or types within the region.

Applicability: Comparative studies are well suited to all the types of estuarine systems within the District, tidal rivers, lagoons, and forested coastlines. Specific comparative studies could be expected to indicate quite clearly which specific valued resources might vulnerable to changes in or currently affected by nutrient status or freshwater inflow in some systems. Regional comparative studies might be able to describe a relationship between nutrient levels and primary production in this area similar to that described by Garber and Boynton, 1991, in the Chesapeake Bay.

Data Requirements: Global or regional comparative studies can often be conducted using historical data. Specific studies, almost by definition, seem to require the acquisition of new data specific to the question at hand. For specific studies comparative data should be collected in very similar circumstances and as nearly contemporaneously as possible in all the systems under consideration.

Logistics and Costs: The resource demand of a comparative study depends on the type and goal. Data and literature reviews and statistical analysis to accomplish a global or regional study may be relatively low in cost. Specific studies including intensive field work and sample analysis as well as statistical and conceptual analysis may require a significant commitment of resources.

Diagnostic Features: Comparative studies can be a very rich source of valuable management information. They can provide indications of solutions to specific problems as well as insights into the processes and characteristics of estuarine systems and the organisms that inhabit them.

Summary: Comparative studies could be a very rich source of information about the estuaries of South Florida. If unimpacted systems are available for study, specific comparisons can be extremely effective in pinpointing the causes and effects of specific problems. Comparative studies which look at all the estuaries of South Florida seeking to find significant differences and commonalities may be a valuable tool for the understanding and management of these systems. Some comparative studies, however, can be resource intensive and require relatively long term commitments.

Segmentation:

Description —
Segmentation, or the geographic partitioning of a study area, is a useful tool in the design of research and monitoring programs. Segmentation recognizes variations and gradients that occur naturally in a coastal landscape. It simplifies and makes explicit assumptions about stratification in the design of statistical analyses, and allows for the equitable distribution of effort to be tested among and between segments. The process also allows for some geographic areas to receive unique monitoring or research efforts.

Depending upon the end-use of the segments, geographic areas may be defined on the basis of a few or many distinguishing features. Florida Bay's separate carbonate and oolite sediment regions illustrate a single geological basis for geographic segmentation. In Tampa Bay, segments have been based on multiple features of depth, circulation, and distance to the Gulf of Mexico. Segmentation of Sarasota Bay, for the National Estuary Program, employed the additional consideration of "problemsheds," or foci of human activity deserving special monitoring attention.

Critique —
Performance: Segmentation is a widely-used tool in a variety of environmental and estuarine sciences, bay management programs, and planning efforts.

Empirical Properties: Segmentation is a geographic divisioning of a study area. Segments therefore have boundaries. Some studies also specify nodes or centroids of segments. All are defined in terms of latitude and longitude, universal transverse mercator units, metes and bounds, or other accepted reference systems.

Applicability: Bays have been segmented for a range of uses in science and management. The most recent and interesting has been "marine zoning"-- or the prescription of certain areas in a bay for particular uses.

<u>Data Requirements</u>: Segmentation relies heavily on existing information to match bay regions to monitoring and research effort, although it is possible to conduct scoping studies or reconnaissance surveys upon which a preliminary segmentation system can be based. Elements of surveys made for such purposes depend largely on the questions upon which new monitoring or research will be based: a detailed study of sediment contaminants, for example, would seek to map Bay depths, granulometry, and circulation patterns as input to a segmentation scheme, but data on living resources might not be initially as important. As outlined in Chapter 1, considerable data exist for the Estero Bay area. Data of the types and kinds needed for segmentation are fewer because historic effort has not been uniformly dispersed across the Bay; changes in historic conditions are believed to have occurred, but are not completely documented as yet, and even the boundaries of Estero Bay's watershed are changing as new data are analyzed.

<u>Logistics and Costs</u>: Segmentation is uncomplicated and inexpensive where sufficient existing data are available.

<u>Diagnostic Features</u>: Perhaps the most unique feature of segmentation as a tool in ecology and management is its nature to cause all parts of an estuary to receive at least some attention, in proportion to its size, occurrence in it of a particular resource or problem, or other criterion. Many other methods have the tendency to concentrate on only a few geographic sub-areas of an estuary.

<u>Summary</u>: Segmentation is useful as a tool to a) organize existing information for an estuary, b) identify geographic areas where data gaps need to be filled, c) assure balance in the distribution of sampling and measurement effort, d) provide a spatial system for normalizing or otherwise standardizing survey results, and e) simplify the presentation of results.

Spatial Analysis --geographic Information Systems:

Description —
Geographic information systems (GIS) are computer programs that allow for spatial information to be recorded, manipulated, analyzed, and presented. A GIS enables users to produce computerized maps. A given map is comprised of multiple layers, or coverages, which are independently stored in the GIS. Thus, a city map may be constructed from coverages on topography, streets, buildings, lakes and rivers, and flood zones. Other coverages provide labels to identify mapped features. Coverages are interchangeable, allowing for a large number of combinations. Scales may vary, allowing users to "zoom" in or out.

GIS coverages presently exist for a large and still-growing number of terrestrial attributes. the number of aquatic, estuarine, or marine coverages are few by comparison, and their number is increasing at a much slower rate. Estuarine ecologists using GIS typically have shoreline, depth, and possibly seagrass coverages available for immediate use, but must create new coverages for most other under-water attributes, even in shallow waters. This means that GIS programs must be used that allow for new polygons (lines tracing out the location of an oyster reef, for example) to be defined in digital format.

A variety of GIS products are in use. One popular system is the ArcInfo System. It provides a module called ArcCAD (computer assisted drafting) for the creation of new coverages; ArcView, a tool for resource managers and others to manipulate existing coverages; and Spatial Analyst. Spatial Analyst is a query system that enables users to perform higher-order analyses of spatial data. A typical command might be, "Display in map format all mangrove wetlands that are within 500 ft. of the Bay, are privately owned, are larger than 30 acres, and more than one mile from a four-lane highway." Other analyses can utilize numerical data, such as water quality measurements, associated with particular points, lines, or areas in a digital map.

Critique —

Performance: GIS is widely used in government, industry, and education. The majority of applications has been terrestrial in orientation, and descriptive in end use. GIS has not been used extensively in marine environments and higher-order analyses are still rare. It is nearly impossible to eliminate mistakes in coverages shared among many users. In this sense, GIS perpetuates mistakes more often than other media.

Empirical Properties: GIS, like segmentation, involves geographic divisioning of a study area. Segments have boundaries defined in terms of latitude and longitude, universal transverse mercator units, metes and bounds, or other accepted reference systems.

Applicability: GIS is broadly applicable to estuarine science and resource management problems.

Data Requirements: GIS interfaces exist that allow for the assimilation of satellite imagery and aerial photography. Inputs are also possible from global positioning systems and a large number of field instruments.

Logistics and Costs: GIS can be operated on personal computers using low-end systems, or on work stations connected via networks to mini-computers or main frame computers running very sophisticated GIS programs. To the extent that ArcInfo may become the standard for most professional GIS, medium to high expenditures and staff training programs should be expected.

Diagnostic Features: The power of GIS is its ability to render large amounts of spatial information, relate it to quantitative data, and produce unique analyses of complex structures and processes.

Summary: GIS has already become a working tool in ecology and resource management. Its application to underwater environments and problems has only just begun.

3.4 Synthesis

Method Applications to Research Questions

Research questions and methods frame the types of investigations needed to complete lines of evidence leading *from* valued ecosystem components *to* management decisions and actions affecting fundamental processes such as freshwater inflow, nutrient enrichment, or contaminant loading. Thus, the underlying rationale for methods posed in this chapter is that each has particular strengths and weaknesses that make it more or less appropriate for research questions posed in Chapter 2.

For purposes of this research program, Estero Bay's valued ecosystem components were identified in Chapter 1 as submerged aquatic vegetation, shellfish, and oligohaline habitats. Goals identified in Chapter 1 posit the management end-points desired for each VEC. Nineteen questions were identified in Chapter 2 as both necessary and sufficient to establish the status and trends of each VEC, as well as relate the VECs to their respective ecological stressors. Some of the 19 questions also link the status and trends of ecological stressors to the controlling effects of physical, hydrological, and chemical processes. The relationship of methods described in the present chapter, to the research questions, is explored below. As before, submerged aquatic vegetation is used as an example.

STQ. 1. What was the pre-development status of valued ecosystem components, in terms of... SAV area, location, depth, species composition, and condition?

STQ. 2. What changes in valued ecosystem components have occurred from pre-development to modern time, in terms of... SAV area, location, species composition, and condition?

Trend Analysis is indicated as the method of choice for these questions, augmented with segmentation and GIS tools.

STQ. 3. What are the geographic and seasonal distributions (and other statistical properties) of measured values for the following stressors regulating valued ecosystem components, *specifically for open Bay waters*: water temperature, salinity, light attenuation, color, chlorophyll, mineral and organic turbidity, nutrients, current speed, wave energy, sediment structure, and tidal exposure values (for SAV)...?

STQ. 4. How have statistical descriptors of present-day stressors changed over the period of available data, for SAV...in the Bay?

Trend Analysis should be combined with Standards, Indices, Typical Values and Nutrient Dilution Curves to answer these questions. Mass balance and box models also are appropriate.

STQ. 5. What are the ranges, statistical distributions, and seasonal and spatial variations of present-day fresh water flow to the Bay, in terms of,

a. direct precipitation,
b. gaged surface water discharge via waterways,
c. ungaged surface water discharge via waterways,
d. sheet flow,
e. water table and surficial aquifers,
f. confined aquifers, and
g. permitted point and non-point source discharges.

STQ. 6. How have statistical descriptors of present-day fresh water flow changed over the period of available data?

Trend Analysis and Modeling can be performed in geographic segments to address these questions.

STQ. 9. What are the present-day spatial characteristics of Bay sediments with respect to:

a. age, provenance, transport, and deposition,
b. thickness, granulometry, and mineral composition,
c. organic content and oxygen demand, and
d. anthropogenic contaminant concentrations?

STQ. 10. What changes in sediment characteristics have occurred in recent times?

Trend Analysis methods augmented with Indices, Typical Values, and Models are indicated.

CPQ. 1. What major physical changes have occurred in the study area, in terms of:

a. topography of the watershed, and
b. bathymetry of the Bay, its tributaries, or Gulf connections?

Trend Analysis is sufficient to answer this question.

CPQ. 2. What are the present-day seasonal requirements and limits of SAV (species diversity, shoot density, biomass, net production, etc.)... in statistically significant terms of... water temperature, salinity, light availability, nutrients, current speed, wave energy, sediment structure, and tidal exposure values...?

As a causal issue, this question is best answered by using Indicator Species, VEC Analysis, and Bioassay & Mesocosm methods.

CPQ. 3. Is physical recruitment a significant factor limiting SAV...abundance and production in the Bay? How?
CPQ 4. Do biological interactions regulate valued ecosystem components more than abiotic stressors, specifically in terms of epiphytic or drift macroalgal inhibition of SAV...?
CPQ. 9. Is sea level rise a significant factor affecting valued ecosystem components in the Bay, in terms of... decreasing maximum depths of submerged aquatic vegetation?

Mesocosm studies are indicated for CPQ's 3, 4, and 9.

The SAV example illustrates that some methods, such as Trend Analysis, are useful for a number of questions, while other methods such as Mesocosms, are uniquely suited to specific questions. Table 2 illustrates the correspondence of methods to the research questions posed for Estero Bay.

Table 2. Distribution of recommended research methods by question and valued ecosystem component (VEC), salinity, and water quality. SAV, submerged aquatic vegetation; S, shellfish; OH, oligohaline habitat.

Research Question	**VEC**	**Applicable Research Methods from Table 1**
STQ 1	SAV,S,OH	1B, 5, 6A
STQ 2	SAV,S,OH	1B, 5, 6A, 6B
STQ 3	none	1A-E, 6A
STQ 4	none	1A-E, 6A, 6B
STQ 5	none	1A-D, 3A, 3B, 6A

STQ 6	no	1A-D, 3A, 3B, 6A, 6B
STQ 7	no	1A-E, 6A
STQ 8	no	1A-E, 6A, 6B
STQ 9	no	1B-D, 2A, 5, 6A
STQ 10	no	1 B-D, 2A, 5, 6A, 6B
CPQ 1	no	6A, 6B
CPQ 2	SAV,S,OH	2A, 2B, 4A
CPQ 3	SAV,S	2A, 2B, 4A
CPQ 4	SAV,S	2A, 2B, 4A
CPQ 5	SAV,S	1B-E, 2, 3, 6A
CPQ 6	SAV,S,OH	1-6
CPQ 7	S	2A, 3C
CPQ 8	S	2A
CPQ 9	SAV,S,OH	1A, 2A, 3C, 5, 6B

Note: STQ, status and trend question; CPQ, causal process question.

3.5 Discussion

A variety of tools are available to answer research questions posed for Estero Bay. The usefulness of many has been demonstrated by past and ongoing studies in and near the Bay. Descriptive methods are relevant to many of the Status and Trends Questions, whereas more complex methods are appropriate for the Causal Processes Questions.

Standards will be meaningful in the context of shellfish propagation and harvesting. Standards will not be relevant for seagrass or oligohaline habitat goals. Trend Analysis will be an important method for Estero Bay studies. Trends must be sought along the length, breadth, and depth of the Bay for a number of attributes related to valued ecosystem components. Trends through time must also be sought, posing a serious research challenge to reconstruct historical conditions in the absence of data. Indices will be more useful for seagrass and shellfish than for oligohaline habitats, whereas Typical Values can be used for research questions on all three VEC goals. Nutrient Dilution may be very informative for oligohaline and seagrass habitat studies.

Many of the species-specific studies envisioned for the Estero Bay Research Plan will utilize methods described previously as Indicator Species, VEC Analysis, and Bioassays and Mesocosms. Particular studies are being designed for bacterial pathogens, macroalgae, seagrasses, oysters, clams, and benthic invertebrates generally.

Mass Balance Models will be useful in water budgets for the Bay; accounting for nutrients and sediments, and perhaps accounting for contaminants. Box Models may be useful in the same applications. Further study is needed before a recommendation can be made to undertake hydrodynamic, salinity, or water quality modeling in the Bay.

Segmentation is already in use by Bay scientists, and additional segmentation systems may be appropriate for studies of each valued ecosystem component. By the same token, geographic information systems are powerful tools for data representation and assessment, especially Spatial Analysis.

Comparative Studies must be crafted with care. As previous chapters have shown, the Bay is unusual with respect to its geometry and hydrology. Comparisons may be useful where Estero Bay is regarded as an end-member rather than a representative member of conditions found in nearby estuaries.

3.6 Chapter 4 Preview

Chapter 4, the final chapter of the Estero Bay Research Plan, will be comprised of a set of individual research projects corresponding to the research questions posed in Chapter 2. Each will employ one or more of the methods described in this Chapter. The project descriptions will follow a standardized format that identifies the goal and research question to which it responds; sets forth the types of data required for its completion; establishes logistical and quality assurance objectives, and indicates how results are to be interpreted and presented. Some will be "bundled" as integrated sets in recognition of their technical similarity or inter-dependence.

Research projects described in Chapter 4 may be thought of as the technical elements of a "Request For Proposals", available to the South Florida Water Management District, Estero Bay Agency on Bay Management, or other agency to employ in furtherance of the Estero Bay and Watershed Management and Improvement Plan.